FIELD EFFECT MEASUREMENTS ON GaAs

D. N. BOSE

DPARTMENT OF PHYSICS, JADAVPUR UNIVERSITY. CALCUTTA-32, INDIA

(*Received March* 7, 1967)

ABSTRACT. Field-effect measurements were performed on 1·5Ωcm. n type GaAs between 150°K and 298°K. The 50 c/s field-effect mobility μ_{fe} was found to be 250 cm²/volt-sec. at 298°K and varied as 1/T with temperature with hysteresis effects occurring at low temperatures. D. C. field-effect relaxations could be observed at low temperatures only and showed pronounced asymmetry. The conductance minimum could not be observed but the presence of depletion could be inferred. No ambient dependence of the field-effect was found suggesting the presence of trapping states within the space charge region. Electron-irradiated specimens were found to have μ_{fe}= 3500 cm²/volt-sec, almost equal to the bulk mobility.

Although there have been a considerable number of investigations on the surface properties of group IV semiconductors germanium and silicon, the III-V compounds which have similar bulk properties have been given comparatively little attention.

Eaton *et al* (1962) reported measurements on p type InSb and found these surfaces to be p type. The first measurements on GsAs were carried out by Gerlich (1962) on n type material. He was unable to observe the minimum of the conductance in the field-effect curve but from the direction of the change of conductance concluded that an accumulation layer existed on the surface. He estimated a fast state density of $3.10^{11}/\text{cm.}^2$.

Pilkuhn (1964) was able to observe the conductance minimum at low frequencies 0.6-1.0c/s but not at higher frequencies. The conductance changes were very small at the low frequencies corresponding to a field-effect mobility of 3.5 cm²/volt-sec compared to a value of 1400 cm²/volt-sec at 8kc/s. At low frequencies the surface appeared to be very close to the conductance minimum and on the majority carrier n type side. Hence a depletion layer condition was considered to exist. As the surfaces of n type material were found to be insensitive to ambient changes the low field-effect mobilities at low frequencies were attributed to acceptor states not on the surface but within the space-charge region trapping the induced charge. P type specimens were found to be essentially different in that they were influenced by ambient and there was an absence of slow trapping.

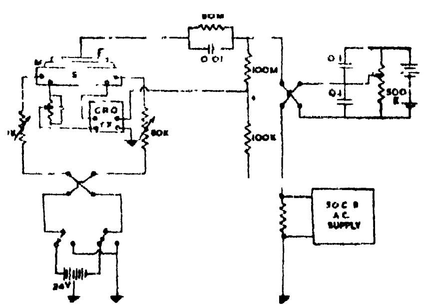
Flinn and Emmony (1963) and Flinn and Briggs (1964) also found evidence for depletion or inversion layer conditions on n type material. The surface-conductance minimum could not be located by surface potential and was estimated from measurements of surface photo-voltage. The surfaces were found to be sensitive to ambient changes.

In the experiments reported here the field-effect mobility was measured at 50 c/s from room temperature, 298°K, down to 150°K. The effect of d.c. and pulsed fields as well as ambient changes were investigated. Finally some experiments were carried out on electron-irradiated specimens which had additional bulk defect levels introduced.

EXPERIMENTAL TECHNIQUES

Samples used were prepared from n type material having bulk resistivities of 1-5Ω cm at 300°K corresponding to carrier concentrations of $12.5\text{-}2.5 \times 10^{14}/\text{cm}^2$. Difficulty was encountered in making suitable electrical contacts to the specimens, best results being obtained using indium pellets etched in H_2SO_4 which were diffused into the GaAs by heating in vacuum at 250° for 2-3 hours. The surfaces were polished with Aloxite and etched in a standard peroxide etch containing 1 part by volume of H_2O_2, 3 parts H_2SO_4 and 1 part H_2O.

Specimens were placed in a cryostat which could be cooled to 150°K. A field-electrode of conducting glass was placed above the upper surface of the specimen separated from it by a 30μ mylar spacer and provision was made for the application of 50 c/s, d.c. and pulsed voltages to the electrode. The field-effect circuit used was described by (1955) Low and is shown in fig. 1. Modulation of the



F = Field electrode
M = Mylar spacer
S = Specimen

Fig. 1. Field-effect curcuit

specimen conductance by the applied field, when a constant specimen current is passed, gives rise to an output signal voltage which is fed to the vertical plates of a high-gain differential input oscilloscope. The horizontal plates are supplied by a signal derived from the field voltage and the horizontal deflection is thus propoertional to the induced charge on the specimen surface. The slope of the field effect curve is therefore proportional to the field-effect mobility :

$$\mu_{fe} = \frac{\Delta G_s}{\Delta \sigma}$$

where ΔG is the change in surface conductance in *mhos*/□ and $\Delta\sigma$ is the induced charge in coulombs/cm^2.

RESULTS

At 298°K the field-effect curve using 50 c/s was a closed line and $\mu_{fe} = 250$ cm^2/volt-sec at the field-free point, compared with a value of 550 cm^2/volt-sec. found by Flinn and Brigges (1964) from 50 c/s to 30 kc/s. From the sign of the slope of the field effect curve the surface was found to be n type on all the four specimens examined, there being no indication of a conductance minimum. Hence evaluation of surface potential as for germanium was not possible. No change in conductance due to d.c. voltages of 1.2 kv. could be detected at 300°K suggesting the presence of a high density of slow surface states, greater than the maximum induced charge density of 10^{12}/cm^2 In contrast with germanium, no ambient dependence of the 50c/s field-effect could be detected using water vapour and ozone. This suggested that the states responsible for the slow trapping were not situated at the interface, but may be bulk trapping states within the surface space-charge region as postulated by Pilkuhn.

As the temperature was lowered the 50c/s field-effect curve developed hysteresis loops as shown in fig. 2a. and the field-effect mobility as measured by the slope at the field-free point was found to increase as shown in fig. 2b. The increase followed the $1/T$ law proposed by Ehrenricich for changes in bulk mobility

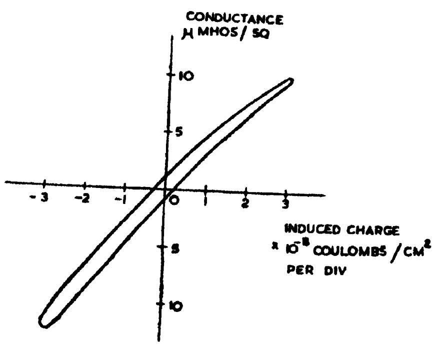


Fig. 2a. 50 c/s field-effect at300°K

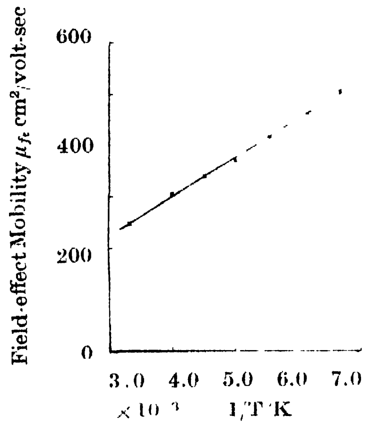


Fig. 2b. Varation of μf_e with temperature

with temperature and could hereby be explained. At 150°K changes in conductance due to applied d.c. fields were evident indicating an increase in the trapping time of the slow states. The conductance changes due to d.c. fields exhibited assymetry as shown in fig. 3. With positive voltages attracting electrons to the surface, the change in conductance was relatively small and the time-constant was 50 msec; with negative voltages repelling electrons from the surface the conductance change was large and of time-constant 500 msec.

Pulsed fields were next applied in order to obtain more information about the time-constants of the trapping states. A time-constant of 500 msec. at 150°K was found to be present, but a more detailed investigation was not possible due to the small magnitude of the signals available.

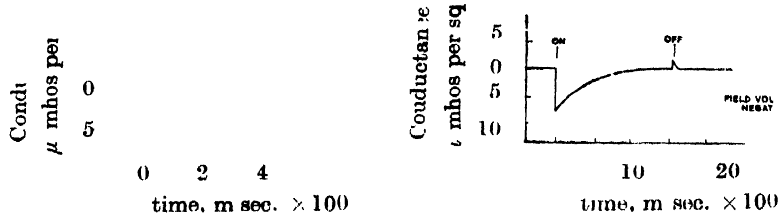


Fig. 3. D. C. field-effect.

Because of the unavailability of material with low carrier concentrations which would provide larger field-effect signals, some additional experiments were carried out on electron-irradiated GaAs. While studying radiation damage in GaAs Grimshaw and Banbury (1964) had noticed changes in surface conductance in addition to bulk changes caused by the introduction of acceptor levels. In the present experiment specimens with initial carrier concentration of $3.10^{16}/cm^3$ at 300°K showing no measurable field modulation of conductance were irradiated with 1.0 Mev electrons thus introducing bulk acceptor levels 0.2 eV below the conduction band as found from optical absorption measurements by Pegler and Banbury. The free electron concentration was thus decreased to $6.10^{15}/cm^3$. Hall effect mobilities before and after irradiation were measured and found to be 4040 and 3260 cm^2/volt-sec respectively, the decrease being due to increased scattering by the acceptor levels introduced. The specimens were irradiated alternately from each side to achieve a more uniform distribution of damage. A calculation of damage rate vs. depth shows that appreciable non-uniformity will remain however as the sample thicknesses were 0.3-0.4 mm. The defect concentration will therefore increase towards the surface and this is liable to invalidate barrier calculations. The surfaces examined after irradiation were again found to be n type with no indication of a conductance minimum present, but the field-effect mobility at room temperature was found to be 3200 cm^2/volt-sec. an order of magnitude higher than on unirradiated specimens, and almost equal to the bulk mobility.

DISCUSSION

GaAs differs from germanium and silicon in that the intrinsic carrier concentration at room temperature is every small, $10^7/cm^3$. Since the impurity concentration is generally $<10^{14}/cm^3$, minority carriers are virtually nonexistent in the bulk. The absence of the conductance minimum in the field-effect may therefore be due either to the surface being far from an inversion layer condition or due to an inadequate generation of minority carriers as the surface is swept through the minimum by the induced field. As the diffusion length of minority carriers in GaAs is also very small the diffusion of carriers from the bulk to the surface would be insufficient to maintain equilibrium. Thus for a rate of inducing positive charge large compared to the minority carrier generation rate the effective field-effect mobility would be determined by the majority carrier and no conductance minimum would be apparent. At a sufficiently low frequency of inducing field minority carriers may be generated to maintain equilibrium and the conductance minimum would be observable. This would explain the hysteresis effects observed in the field-effect curve at low temperature and Pilkuhn's results qualitatively.

Pillkuhn did not attempt a more quantitative analysis of his results. The importance of the generation of minority carriers through localised centres can be estimated from the following analysis. Neglecting recombination through traps and considering band-band transitions alone, it is possible to calculate the generation rate of carriers at room temperature. For a carrier concentration $n = 2.10^{15}/cm^3$ Hilsum and Holeman (1960) found a minority carrier lifetime of 10^{-9} secs. From this the generation rate of minority carriers is found to be $10^7/cm^3$ sec. at room temperature. The rate required to maintain equilibrium in Pilkuhn's experiment at 0.6 c/s as calculated from his field-effect curves is much larger $10^{11}/cm^3/sec$. The large difference shows that generation of minority carriers proceeds mainly through localised centres and not by band-band transitions. The asymmetrical d.c. field-effect characteristic can likewise be attributed to inadequate minority carrier generation. When a negative voltage is applied, electrons are repelled from the surface and the generation time of holes determines the relaxation time-constant. With a positive voltage applied, the electons required are supplied from the bulk at a much faster rate. Thus although the field-effect curve shows a n type surface with no sign of the minimum, the hysteresis effects at low temperature and the d.c. field-effect are characteristic of a two-carrier process supporting the idea that the surface is not in an accumulation layer but in a depletion layer condition.

The large difference between the field-effect mobility on irradiated and unirradiated specimens is difficult to explain but may be due to loss of negative charge from surface states as found by Spear (1958) on germanium surfaces irradiated by 5Kev-4.5Mev electrons. An increase in the electron concentration in the space charge region would thus occur, which might convert the depletion layer initially present into an accumulation layer As the field-effect mobility approaches the bulk mobility, a very small density of screening states would have to be postulated at the new value of surface potential. In view of the difficulty in identifying surface states on germanium with states within the space charge region postulated in GaAs, it is not possible to go further without more direct measurements.

ACKNOWLEDGMENTS

The author is indebted to Dr. P. C. Banbury for helpful discussions, to Prof. R. W. Ditchburn for the provision of laboratory facilities and to I.C.I. (India) Private Ltd., for the grant of a Technical Scholarship.

REFERENCES

Eaton, G. K., King, R. E. J., Morton, F. D., Partridge, A. T., and Smith, J. G., 1962, *J. Phys. Chem. Solids* **15**, 117.

Flinn, I., and Briggs, A., 1964, *Proc. Int. Comf. on Phys. and Chem. of Solid Surfaces*, Brown University, 136.

Flinn, I. and Emmony, D. C., 1963, *Phys. Letters* **6**, 133.

Gerlich, D. 1962, *J. Appl. Phys.* **33**, 1815.

Grimshaw, J. A. and Banbury, P. C., 1964, *Proc. Phys. Soc.* **84**, 151.

Pilkuhn, M. H., 1963, *J. Phys. Chem. Solids* **25**, 141.

Spear, W. E., 1958, *Phys. Rev.* **112**, 362.

Hilsun, C., and Holeman, B., 1960, *Proc. Int. Conf. on Seoniconductor Physics*, Prague,

Low, G. G. E., 1955, *Proc. Phys. Soc.* (*London*), **B680**, 10 1154.